An Observing System Simulation Experiment for Hydros Radiometer-Only Soil Moisture Products

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***Abstract*—Based on 1-km land surface model geophysical predictions within the United States Southern Great Plains (Red-Arkansas River basin), an observing system simulation experiment (OSSE) is carried out to assess the impact of land surface heterogeneity, instrument error, and parameter uncertainty on soil moisture products derived from the National Aeronautics and Space Administration Hydrosphere State (Hydros) mission. Simulated retrieved soil moisture products are created using three distinct retrieval algorithms based on the characteristics of passive microwave measurements expected from Hydros. The accuracy of retrieval products is evaluated through comparisons with benchmark soil moisture fields obtained from direct aggregation of the original simulated soil moisture fields. The analysis provides a quantitative description of how land surface heterogeneity, instrument error, and inversion parameter uncertainty impacts propagate through the measurement and retrieval process to degrade the accuracy of Hydros soil moisture products. Results demonstrate that the discrete set of error sources captured by the OSSE induce root mean squared errors of between 2.0% and 4.5% volumetric in soil moisture retrievals within the basin. Algorithm robustness is also evaluated for the case of artificially enhanced vegetation water content (W) values within the basin. For large $W(> 3\ \mathrm{kg}\cdot\mathrm{m}^{-2})$, a distinct positive bias, attributable to the impact of sub-footprint-scale landcover heterogeneity, is identified in soil moisture retrievals. Prospects for the removal of this bias via a correction strategy for inland water and/or the implementation of an alternative aggregation strategy for surface vegetation and roughness parameters are discussed.**

***Index Terms*—Microwave remote sensing, observing system simulation experiment, soil moisture, spaceborne radiometry.**

Manuscript received July 16, 2004; revised January 19, 2005. This work was supported by the National Aeronautics and Space Administration (NASA) Earth System Science Pathfinder (ESSP) Program Risk-Mitigation Phase funding to the Hydros Science Team. The high-resolution land surface modeling approach and forcing dataset used in this analysis were developed under the direction of E. Wood at Princeton University through support from NASA under Grants NAG8-1517 and NAG5-6494 and from the National Oceanic and Atmospheric Administration under Grant NA96GP0413. The research described in this paper was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

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Digital Object Identifier 10.1109/TGRS.2005.845645

I. Introduction

An IMPORTANT issue in the development of a dedicated spaceborne soil moisture sensor has been concern over the reliability of soil moisture retrievals in densely vegetated areas and the global extent over which retrievals will be possible. Errors in retrieved soil moisture can originate from a variety of sources within the measurement and retrieval process. In addition to instrument error, two key contributors to retrieval error are the masking of the soil microwave signal by vegetation [1], [2] and the interplay between nonlinear retrieval physics and the relatively poor spatial resolution of passive microwave spaceborne sensors [3]–[6]. Quantification of these errors requires the realistic specification of land surface soil moisture heterogeneity and spatial vegetation patterns. Since detailed soil moisture patterns are currently difficult to obtain from direct observation, an attractive alternative is the application of an observing system simulation experiment (OSSE) in which simulated land surface states are propagated through the sensor measurement and retrieval process to investigate and constrain expected levels of retrieval error [7], [8].

This analysis describes an OSSE performed for soil moisture products to be derived from the NASA Hydrosphere State (Hydros) mission. The Hydros mission is an Earth System Science Pathfinder (ESSP) mission selected in 2002 by NASA for further development and currently scheduled for launch in 2010 [9]. Hydros is designed to provide global maps of the earth's soil moisture and freeze/thaw state every 2–3 days for weather and climate prediction, water, energy, and carbon cycle studies, and natural hazards monitoring. Hydros utilizes a unique active and passive L-band (1.2–1.4 GHz) microwave concept to simultaneously measure microwave emission and backscatter from the surface across a wide spatial swath [9], [10]. The Hydros antenna is an approximately 6-m diameter deployable lightweight mesh reflector that provides footprint sizes of approximately 40 km for the radiometer and 30 km for the radar. The radar resolution is enhanced to 1–3 km using synthetic aperture processing. The key derived products are soil moisture at 40-km resolution for hydroclimatology obtained from the radiometer measurements, soil moisture at 10-km resolution for hydrometeorology obtained by combining the radar and radiometer measurements in a joint retrieval algorithm, and freeze/thaw state at 3-km resolution for terrestrial carbon flux dynamics studies obtained from the radar measurements.

For the OSSE described in this paper, we focus on the 40-km soil moisture product, and use a baseline set of passive microwave retrieval algorithms to illustrate Hydros retrieval capabilities and examine error propagation in the algorithms. The synthetic experiment is driven by realistically heterogeneous land surface geophysical variables generated from a distributed land surface model. These states are used to derive a set of simulated brightness temperatures which are degraded (i.e., spatially aggregated and randomly perturbed with simulated instrument noise) to simulate Hydros measurements and then inverted back into soil moisture products using various retrieval algorithms. Comparison of these retrievals to the original soil moisture field reveals how the performance of soil moisture retrieval algorithms will be impacted by vegetation density, measurement resolution, inversion parameter uncertainty, and land cover heterogeneity. The intent of this analysis is not to capture the full range of error sources impacting the accuracy of spaceborne soil moisture retrievals. Rather, it is to study the error propagation of a discrete number of error sources through the entire Hydros observation and retrieval system and examine prospects for remediation strategies to reduce the impact of these errors on Hydros soil moisture products. OSSE-type experiments provide a controlled-synthetic environment within which such issues can be addressed prior to sensor launch. The comparison of results in this paper obtained from different retrieval algorithms is not intended as a selection test for the algorithms but as a means to investigate the sensitivities of the different algorithm types to the error sources studied in this OSSE. Continuing evaluations of these and other algorithms will be performed in the years ahead, using a variety of simulation and observational datasets, for further algorithm optimization and selection prior to the launch of Hydros. This particular study focuses exclusively on 40-km Hydros soil moisture products derived from radiometer observations and passive-only soil moisture algorithms. Future work will focus on higher resolution Hydros products derived from radar observations.

X. Discussion and Conclusion

The observing system simulation experiment described here captures the influence of land surface heterogeneity, observation noise, inversion parameter uncertainty, and retrieval assumptions on the accuracy of radiometer-only Hydros soil moisture products. Examining these error sources in a controlled numerical setting provides an opportunity to assess eventual processing and retrieval strategies designed to mitigate their impact. Nevertheless, care should be taken when equating error results presented here to accuracy expectations for actual Hydros soil moisture products. This particular OSSE provides a simplified representation of only a partial set of error sources within actual retrievals. Particular choices concerning the nature of represented error may impact the relative accuracy of various retrieval algorithms. For instance, the decision to neglect error in W estimates almost certainly reduces error in algorithm A's soil moisture retrievals but has little or no effect on algorithm B and C's results, which do not explicitly consider vegetation water content. In addition, while useful as a test-bed to study strategies for treating aggregation-based retrieval errors (see Section IX), results for the case of scaled-up vegetation density $(3W)$ should be interpreted as a worst case scenario of land surface heterogeneity and vegetation density encountered over only limited portions of the globe. Hydros soil moisture algorithms will undergo continued evolution and refinement prior to Hydros launch, based on a combination of OSSE results, further analyses, and data from ongoing airborne field campaigns. Given the generally large contribution of retrieval biases to overall RMSE (e.g., see Fig. 7), it may be possible to improve the accuracy of retrieved soil moisture via calibration of retrieval model parameters.

In this analysis, soil moisture products were simulated for three different retrieval algorithms (Section VII), each requiring a different amount of ancillary soil and vegetation information. Within the United States Southern Great Plains, the overall impact of captured error sources on the accuracy of 36-km soil moisture retrievals is between 2.0% and 4.5% volumetric for all three retrieval algorithms (Fig. 5). The impact, however, is more acute for heavily vegetated footprints (Fig. 6).

To study these areas in greater detail, the OSSE was repeated for the case of artificially scaled W values (by a factor of three). The $3W$ case represents a worst case scenario in which land surface heterogeneity—specifically vegetation optical depth variability—is synthetically increased to illuminate the impact of sub-footprint-scale heterogeneity on retrieval accuracy. Retrieval results for the artificially scaled $3W$ case demonstrate positive biases at high W levels [Fig. 7(b)]. Despite relatively low spatial density ($<1\%$ of the basin), failure to account for the impact of inland water on soil moisture estimates contributes significantly to this bias (Fig. 8). The remaining positive bias is due to aggregation impacts associated with applying retrieval algorithms at a footprint-scale (36-km) that is much coarser than the underlying 1-km resolution of the geophysical fields used to force the OSSE (Fig. 9). Measurement noise and simplifying retrieval assumptions appear to play a lesser relative role.

Aggregation impacts are particularly strong at high W when using algorithm A, which derives 36-km soil and vegetation values based on the direct aggregation of 1-km fields. For $W < 6\,\mathrm{kg\cdot m^{-2}}$, utilizing either regression (algorithm C) or the simultaneously fitting of parameters to T_{Bv} and T_{Bh} observations (algorithm B) to derive effective footprint-scale W appears to offer a partial correction for aggregation errors (Figs. 8). Algorithm B utilizes an alternative strategy and derives effective 36-km W values based on numerical fitting to T_{Bv} and T_{Bh} observations. Negative biases in effective W derived in this manner partially counteracts the prevailing positive bias in soil moisture retrievals (Fig. 10) and may represent a preferential strategy for aggregating heterogeneous W fields up to footprint-scale resolutions. Consequently, strategies that solve for effective W values based on multipolarization observations (e.g., algorithms B and C) may have some advantages for highly heterogeneous footprints. However, more information is needed to determine how robust these approaches, particularly the empirical vegetation correction strategy in algorithm C, will be in real operational environments.

The OSSE also clarifies the potential of two operational data processing strategies to reduce the impact of land surface aggregation errors. Given knowledge of fractional water coverage, the impact of nonresolved water bodies on soil moisture retrievals can be effectively filtered using (23) (Fig. 11). However, remaining biases in soil moisture retrievals from algorithm A are problematic in the sense that they cannot be corrected via simple alternative strategies for aggregating static soil and vegetation properties up to the footprint-scale (Section IX-B and Fig. 12). More study on alternative aggregation techniques is required.